

MULTI-COLOR HOLOGRAPHIC ART IMAGING
FROM ONE HELIUM-NEON LASER

By

Donald Karl Thornton

B.A. (Mathematics) Hamilton College

1969

B.F.A. (Painting) Rhode Island School of Design

1974

Submitted in Partial Fulfillment
of the Requirements for the
Degree of

Master of Science in Visual Studies

at the

Massachusetts Institute of Technology

February 1979

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Signature of the Author

Donald Karl Thornton
Center for Advanced Visual Studies
Department of Architecture
January 19, 1979

Certified by

Otto Piene
Otto Piene, Professor of Environmental Art;
Director, Center for Advanced Visual Studies, Thesis
Supervisor

Accepted by

Nicholas Negroponte
Professor Nicholas Negroponte, Chairman
Department Committee for Graduate Students

Rotch
MASSACHUSETTS INSTITUTE
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Multi-Color Holographic Art Imaging
from One Helium-Neon Laser

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Submitted to the Department of Architecture on February 1979
in partial fulfillment of the requirement for the degree of
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Holographic imaging systems are explained and evaluated with regard to artistic qualities as well as technical difficulties and solutions. The limited parallax white light transmission Benton hologram is examined for fulfillment of the desired qualities in holographic art imaging: polychromatic imagery with few object depth or placement restrictions; reconstruction with white light for brightness and convenience in exhibition; fabrication with a minimum number of lasers and expensive lenses. Multi-color holographic art imaging with three laser wavelengths and one reference angle is described. The complimentary system of multi-color holography from one laser and multiple reference angles is stated, tested and evaluated. Recent optical improvements are evaluated. Actual production of multi-color holographic images from a single laser is recounted. The exhibition is described and photographs of the exhibition and some of the images are included.

Thesis Supervisor: _____

Otto Piene

Title:

Professor of Environmental Art; Director,
Center for Advanced Visual Studies.

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ACKNOWLEDGEMENTS

The author gratefully acknowledges the artistic guidance and research assistance afforded by Otto Piene and H. Casdin-Silver.

Special thanks to H.J. Gerritsen for explanations and for making this research and production possible. The generous legacy of quality techniques left by S.A. Benton is also acknowledged.

Photo credit: Paul Foley.

A general, brief description of holographic imaging systems will establish common ground and allow us to proceed with understanding to the holographic techniques forming the kernel of this paper.

Holographic Imaging Systems

Starting with the seminal laser transmission hologram system, some terms and technical explanations will be established. The discussion will proceed through: image plane transmission holograms; reflection holograms; and limited parallax white light transmission holograms, to multiple color laser transmission and multiple color white light reflection holograms.

1) Laser Transmission Holograms. In a transmission hologram set up the coherent laser light is divided into two parts by a partially reflective, partially transmissive beam splitter. One of these beams lights the object after being spread out by lenses and possibly split into more parts, this beam of light is termed the object beam. The other part of the split laser light is called the reference beam. The reference beam is expanded by lenses and goes directly to the high resolution, slow speed silver halide photographic plate which is normally used as the holographic recording medium. In order to understand what happens when these two beams recombine or interfere at the recording holographic plate, the spatial and temporal coherence properties of laser light are mentioned. Basically, coherent light is well-behaved, pre-

dictable light of one color which comes from and can be returned to a point. The monochromatic quality is called temporal coherence and the other quality is called spatial coherence. This well defined in step or in phase property facilitates the storage of information about the object. The interference or automatic comparison of the laser light wavefront from the object with the reference beam, which remains undisturbed and well known, is how space and luminence information about the object is recorded. To continue with holographic theory it will be instructive to ask a general question which demands a complete and practical explanation of what is happening during exposure of the holographic plate. We all know that a silver halide emulsion is sensitive to light; how is it that a photographic plate which is capable of recording only the differences in the intensity of light is 'tricked' into recording complete spatial information about the object? The answer runs systematically through the necessary parameters to record the position of an object point as a variation of intensity at the emulsion plane. These parameters are chosen as: a) distance of the object point from the holographic plate; b) angle between the reference beam and the object point; c) the relative intensity of the laser light diffused, reflected or transmitted to the emulsion from the object point.

As well as being given by decreasing light intensity with increasing distance and correlation of information from

different parts of the plate, the distance of the object point from the plate is given by the phase of the coherent laser light, roughly the remainder, in fractions of a wavelength, after dividing the distance by the wavelength of the laser light used. More simply, whether the lightwave from that point is at its crest, trough, or in between when it arrives at the plate. This is a measure of the amount of energy or the intensity of the coherent light as it reaches the plate and is recorded by the emulsion.

As the angle between the reference beam and the object, in this example most conveniently a plane surface, increases from zero to almost ninety degrees the interference pattern in the plane of the emulsion goes from a recombination of identical wavefronts, giving even illumination across the plate, to an increasing density of stripes or interference fringes at the plate. This is the familiar interference of wavefronts of coherent light often demonstrated with the Michelson interferometer.

The intensity of each object point is of course directly recorded by the photographic emulsion.

Laser transmission holograms derive their name from the transmission of the reference beam through the plate during recording or reconstruction. The reference beam and the object are on the same side of the holographic plate when the plate is being recorded. To effect reconstruction of the image of the object at the same position in space relative to

the reference or reconstruction beam and the plate, laser light is directed to the developed holographic plate from the same distance and reference angle as the original reference beam. As the laser light goes through the microscopic interference pattern which was recorded on the plate, the light is reflected and diffracted to reconstruct the recorded light wavefronts from the object. The image of the object as it was lit with laser light during exposure of the hologram is reconstructed precisely as it was recorded. This image appearing behind the hologram as an object is called a virtual image. Because the image appears exactly as the object did this image is also described as orthoscopic. If the hologram is turned 180 degrees, or optimally the reconstructing laser light comes from the opposite side of the plate and converges to the original source point of the reference beam, the image is viewed in front of the hologram. This image which is on the same side of the hologram as the viewer and is seen in reverse relief is called a real image and is pseudoscopic.

A second generation hologram can be made of this projected pseudoscopic real image in a manner very similar to the first generation laser transmission hologram. The actual object is replaced by the pseudoscopic real image. The second generation image can be in front of (real), in back of (virtual), or in the plane of (image plane) the new holographic plate.

The second generation plate is almost always turned 180 degrees for reconstruction. This reverses the relief or depth

of the recorded pseudoscopic image producing an orthoscopic or correct looking image. In this manner it is possible to produce second generation holograms one by one from a first generation or master hologram.

To exhibit the first or second generation laser transmission holograms in a convenient set up the hologram recording is generally done with the object on its side. When the plate is rotated (in its plane) 90 degrees the object is upright and the reconstructing reference beam shines from above through the plate. The portion of the reference beam which is not reconstructing the image continues through the plate to the floor. This is a good example of the forethought necessary throughout the process of making and exhibiting a hologram. Some of the restraints just cannot be violated, others are very subtle and result in compromises or exchanges. A few of the less subtle restraints should be explicitly mentioned. Absence of movement or vibration during the time exposure of the holographic emulsion is necessary so that the precise, microscopic interference pattern does not change or become superimposed with a slightly different pattern. This motion restraint includes the entire holographic table, the laser and all optical components, and the object being recorded. If the exposure is in the micro- to nanosecond range this stability requirement can be significantly relaxed. This means having a high quality well tuned and powerful pulse laser available for holography. The other major restraint

is the result of the not quite perfectly coherent light from actual lasers. Several standing frequencies or harmonics resonate in the laser cavity. The resulting periodic combination or beating of these frequencies means that for maximum interference fringe contrast the object and reference beams recombining at the plate must have left the laser at the same time. This translates to the requirement of equal pathlengths for the reference and object beams. The pathlength difference which can be tolerated for acceptable interference pattern contrast is termed the coherence length of the laser. This brief introduction to the terminology and limitations of holographic laboratory systems will enable us to continue in describing holographic imaging systems.

2) Image Plane Transmission Holograms. If the second generation holographic plate is placed through the real, pseudoscopic image projected from the master hologram the second generation hologram is called an image plane hologram. An alternate way to produce an image plane hologram is by using a lens to form a real image of the laser lit object. The holographic plate is placed in this image and a one step image plane hologram is recorded. Considering this placement of image it is apparent that one part of what is happening during the exposure is the recording of a photograph of the image. This photograph may be in focus only for the parts of the image which are actually in the plane of the emulsion. It is also deteriorated as a photographic image because re-

ording three dimensional information requires a reference beam to be directly incident on the plate. But our realization is useful for there are no restrictions on the coherence of light when viewing a photograph. Contiguously the restraints on the coherence of light to reconstruct the image of an image plane transmission hologram are so relaxed that the image can be viewed when reconstructed with a point source of white or incandescent light. Even though the interference pattern or grating bends light proportionally to its frequency or color the light forming an image in the plane of the plate has almost no time to spread out before it forms the image. Consequently the image is barely color blurred if it is formed fairly close to the plate. Trying to reconstruct a deeper image with a white light source would result in confused overlapping images in each color, blurring the object beyond recognition. The light quality of images reconstructed from image plane holograms and the limitations of this imaging method will be considered in the next section. Making and exhibiting image plane transmission holograms is otherwise identical to making and exhibiting second generation transmission holograms.

3) Reflection Holograms. Reflection holograms derive their name from the reflection of the reconstructing light to form the image. This type of hologram is similar to transmission holograms in the way it is set up and composed, except with the reference and object illumination on opposite

sides of the plate. The theory for reflection holograms is significantly more complicated and will be lightly treated here. The interference pattern of these beams form hyperboidal reflecting surfaces, closely packed in nearly the plane of the hologram. The spacing of these reflecting fringes corresponds to the wavelength of the laser light used to make them (or often to a shorter one because the emulsion shrinks when the unexposed silver halide is removed by the fixer during processing). At each layer light is reflected but only light of the wavelength of twice this spacing adds up in phase from successive layers, all other wavelengths destructively interfere being out of phase with the same wavelength light from other reflecting surfaces. This is the selective filtering action which allows reflection holograms to be viewed when illuminated with a point source of white light and is expressed by Bragg's law. Because the reconstructing light comes from the same side of the plate as the viewer sees the image, reflection holograms can be placed flat against the wall when exhibited. As in laser transmission technique this reference light can come from above the hologram plate. In spite of the more complicated theory for reflection holograms, a one beam reflection hologram is among the simplest holograms to make. An object is placed behind the plate holder and the reference beam is directed at an angle to cover the plate. After the reference beam passes through the plate it illuminates the object and is reflected back to the emulsion as the object wavefront.

4) Limited Parallax White Light Transmission Holograms. Although it is possible to make one step limited parallax white light transmission holograms¹ a high quality lens is needed to form an aerial image of the object. Consequently in most holographic art laboratories the second generation technique is used exclusively. The second generation holograms are all holograms of a hologram, called the master. After a word about master plates we will consider "holograms of a distant slit".

A word about master plates. Since the emulsion doesn't see those handy labels we put on the "object" or the "reference beam over this way" signs, it is really quite conceivable for it to mistake a bright spot on the object as the reference beam or reference point. After all, the holographic theory we've learned implies if not clearly states that each point of light which the plate sees interferes with each other point of light. What can we do to clarify this situation and to improve the quality of our second generation holograms? On the standard laser transmission holograms the angle between any point on the object is made larger than the angle between any two points on the object. This means that the spacing of the interference fringes or spatial frequency in the emulsion of the interference between any two object points is much less than the spatial frequency

¹H. Chen and F.T.S. Yu, Opt. Lett. 2,4 (1978).

of the interference between the reference beam and any object point. Thus the crosstalk between the desired information and noise of object point-self interference is minimized. They are recorded on different spatial frequencies. The effect of the ratio between the intensities of the reference beam and the object beam is one of the most important yet hardest to assimilate (i.e. recurring) lessons in holography. An explanation of the film characteristic, a curve graphing the response of the silver halide emulsion to light, shows us that at least a 2:1 ratio is needed to keep the film's response to light in the linear portion of the curve. Interpreting the reference beam as the carrier of the information and therefore to be only modulated by the constructive and destructive interference of the object information lead us, together with some actual ratio tests, to normally settle on a 3;1 ratio. The ratio tests show that the image/information has less noise and becomes cleaner but gets dimmer as the ratio increases. Making the reference beam about three times brighter than the average object light asserts its identity and predominance. Increasing the ratio even more will give cleaner, clearer information at the expense of the brightness of the image on the master plate. Perhaps a bad strategy? No, for the ratio can be reduced for our second generation plate to increase its brightness.

Holograms of a distant slit. This hologram method is the brilliant child of Dr. Stephan A. Benton. The Benton

hologram, sometimes called a "rainbow hologram", is bright because it gathers and images the light from the reconstructing white light reference beam into a rainbow (blurred) stack of slits. Through this spectrum stacked slit image, in front of the plate, the hologram is viewed. Through this stacked slit we gain brightness and are able to reconstruct the image with incandescent and with sun light. Through this slit we sacrifice all vertical parallax information. A second generation limited parallax white light transmission hologram is produced in much the same way as the preceeding second generation laser transmission hologram. The main difference is that the master plate is apertured down to a horizontal slit when the real pseudoscopic image is projected as the object of the second generation hologram. Further explanation and evaluation of the Benton hologram will be reserved for the next section. The exhibition of this hologram can be with a bright light above and behind the plate as the image plane holograms are exhibited.

5) Multiple Color Laser Transmission Holograms and Multiple Color White light Reflection Holograms. That I have had extremely little direct laboratory experience with multiple color holographic processes requiring more than one laser is an indication of the scarcity of such facilities for the visual artist. It is also indicative of the complications and problems prevalent in even the more advanced laboratories. All the preceeding holograms image objects

in a chiaroscuro manner with monochromatic or only slightly controllable spectral color. Natural color or at least controlled full color has always been the pronounced if long range goal of display holography and seems to be within reach. This goal also seems always to be plagued by technical complications and complicated with expensive equipment. Making multiple color laser transmission holograms requires multiple color lasers and usually multiple exposures but it is still very similar to the standard monochromatic laser transmission holograms. Problems more than triple. Even reconstruction of these holograms requires several lasers or multiple wavelength lasers. In the next section the difficulties will be briefly stated and evaluated.

Producing multiple color reflection holograms has similar difficulties but in different proportions minimizing some emphasizing others. They have seemed attractive for their built in wavelength selective filters which eliminate ghost images and enable them to be displayed with a white light source while hanging against a wall.

Evaluation of these Holographic Imaging Systems

1) Laser Transmission Holograms. This type of hologram remains one of the most exciting visual experiences available with holographic art imaging possibilities. There is an undeniable excitement and presence about coherent laser light. This beautiful obviously special and refined light has inherent interest (e.g., speckle from self interference

of adjacent points) and rather exotic mystery (dim exhibition rooms, high technology, and black shrouds). It is characteristic of holography that its qualities are praised then denounced and that its limitations are used as assets. An excellent example of the latter is the use of the strict object movement restraints to produce a contour map of stress or defects in the object. This is a double exposure technique called Non Destructive Holographic Testing. A remaining major asset of laser transmission holograms is the great depth or frontal projection possible without deteriorating the crisp precisely focused image. The requirement for such a coherent light source, making distant imaging possible, is also a considerable deficit. The relative dimness of the image in most exhibited laser transmission holograms is due to both the increased cost of higher powered lasers and the Federal restrictions on lasers stronger than a weak one milliwatt. Filtered arc lamps are often used to reconstruct holograms. The image visibly deteriorates but is usually acceptable and the laser stays in the laboratory.

2) Image Plane Transmission Holograms. This hologram gains relaxed reconstruction light source restrictions at the expense of increased restrictions on object placement and object depth. Consequently during exhibition the trade is pushed the other way as much as possible by reconstructing the image with as perfect a point source as available. As do all second generation holograms and all lens formed one step

holograms, the image plane hologram runs into certain aperture problems. The second generation hologram images the master plate in front of it as a window through which we view the object. An extreme and obvious example would be that a large hologram (window) of a small window (hologram) doesn't increase the available information. Actually when the second generation plate is turned around 180 degrees some distortion occurs in the image and in the real image or aperture of the reconstructed master plate. This lens type magnification and distortion happens because the plate expects to be illuminated from the reference point which is now in front of the plate. This would mean using a large lens to focus the reconstructing light to converge to this reference point. The diverging not converging light illuminating the plate causes the magnification. The distortion caused; the adequate and perfect corrections will be dealt with during the evaluation of the Benton hologram. The quality of the light reconstructing the image in the plane of the hologram plate is quite unique because it contains all the visible wavelengths. There is no speckle typical of coherent laser light. The image is seen in a clear blue white usually with some color blurring as it extends too far from the plate and with slightly reddish or bluish hue changes as the viewer goes up or down respectively.

3) Reflection Holograms. Significant attention is needed when making reflection holograms. What's there is what you get...but!... our eyes see better under difficult

conditions than silver halide emulsions do. Reflections of diverging light blind the plate, especially for reflection holograms. Our eyes see hot spots or hot highlights easier also. This leads to cosmetic alterations of the object (from painting reflective areas flat black, to tilting the object so the reflections don't hit the plate, to raising the ratio). Image plane second generation reflection holograms are usually brighter and have fewer constraints on the white light source needed for reconstruction than do reflection holograms with more depth. Selective wavelength filtering reflects only a small amount of the incident light causing a susceptibility to dim images. Low diffraction efficiencies image the object with only a small fraction of light of the selected color. Brighter object points often cause spectral blurs and as mentioned blind sections of the plate sometimes, even if the object was quite clear to your eye. As an example a string of pearls was not recognizable, because of spectral blurring, until it had been coated with a thin wash of flat black paint. Now looking just like white pearls (in green light), you could see the formerly obscured roundness of each pearl. The aperture problem discussed under image plane transmission holograms is also relevant for second generation reflection holograms. The change in color due to emulsion shrinkage problem with reflection holograms has already been mentioned. This change, to green from red, for example, is usually just accepted. Sometimes chemicals are

used to swell the emulsion. The permanence of this procedure has not been proven but it seems quite stable when sealed with cyanoacrylate and a glass coversheet. Another more advanced method of controlling emulsion shrinkage has been developed by Dr. Benton at Polaroid. This technique will be described during the evaluation of full color reflection holograms. Before evaluating the Benton hologram let us recall that the holograms we have evaluated so far have had full vertical and horizontal parallax.

4) Limited Parallax White Light Transmission Holograms. The Benton Hologram sacrifices vertical parallax by using the information from only a horizontal strip of the master hologram. The length of this slit determines possible angles of view (total horizontal parallax). This is just the return of the aperture or window problem disparaged in a previous section. The (vertical) width of this slit is an even more touchy matter. Since it is the image or attempted image of this slit blurring out into a spectrally stacked slit through which we see the desired object image, the width of the slit imaged in each color controls overlapping. (There is really a continuum of colors or wavelengths and of images.) The aperture of the eye also has an effect perceptually stated: too narrow a slit causes speckle in the object image and too wide a slit blurs the object image. This can be understood as a fairly straight forward result of the self interference of object points lit by quite co-

herent light (narrow slit) and the blurring of object points from polychromatic light (wide slit).

Laboratory sessions put holographic theories into practice. A characteristic "doing-everything-at-once" or "filtering through successive layers of roughing out to fine tuning the set up" soon becomes apparent in the lab. There is nothing like a little empirical testing of any theory to extend your understanding of the theory, the world, and your abilities: the ability to understand, to formulate reasons, iron out problems, and to produce in actual laboratory conditions. While arranging the composition of the second generation hologram care must be taken to get a good hologram of that distant bright slit of the master. The plate should be quasi-parallel to and mostly centered toward the bright slit while still arranging the framing and depth composition as desired. Magnification of the real image from the master plate occurs (as well as considerable astigmatism¹), in most holographic laboratories, because while approximating self-conjugate plane wave reference and reconstruction wavefronts for the master plate, expensive large lenses are needed to get a reconstruction wavefront conjugate to the recording reference wavefront. There will be another round of magnification, astigmatism and focusing

¹S.A. Benton, "White-Light Transmission/Reflection Holographic Imaging", Applications of Holography and Optical Data Processing, ed. E. Marom and A.A. Friesem (Oxford and New York: Pergamon Press, 1977), p. 406.

effects in the reconstruction of the limited parallax white light transmission hologram. The currently pertinent result is that the composition will at the least undergo typical lens magnification effects, enlarging longitudinally as the square of the enlargement which occurs in the plane parallel to the master and second generation plates. Often this gives a composition which looks better on a small plate than it will turn out. The effect the reference angle of the second generation plate has on the spreading of the colors imaging the slit is another important consideration. By increasing the reference angle it is possible to see the image of the object in one color at a time over a considerable viewing range. A reduced reference angle makes it probable that the viewer will see the object in more than one color at a time. Yet another parameter is the distance between the first and second generation plates (this also inevitably leads back to the distance between the object and the master plate). The distance determines where the slit is imaged and the subsequent acceptable viewing distances. The distance is increased by the square of the magnification factor of the slit height and width. A slightly distant and large (longitudinal) viewing range results from a large distance between plates; a closer and quite reduced viewing range results from a short distance. I shouldn't need to explain by this time that as well as a slightly reduced intimacy between image and viewer other things are compromised for increased (long-

itudinal) viewing range. The object must generally be further from the master plate, decreasing available parallax and increasing exposure times.

The real focus of the second generation hologram experience, after practice, playing around, and a few mistakes is a gestalt. Again everything at once, understanding where the master plate's real image is reconstructing in space and what the second generation hologram will look like: an intuitive feeling for composition, magnification and final placement of the image. The important guts of artistic holographic laboratory work is a feeling of being on top, being able to decide the parameters, adjusting and intuiting the change in the final plate. Manipulation and feedback: making changes and seeing what you get in the hologram is the way to enhance the understanding of what image alterations you are making. This will result in a state of being able to teach yourself, a state of understanding enough to tweak the parameters and interpret the result.

Though there are still restrictions on the spatial quality of the white light source and though expensive lenses are desirable for optimal imaging, sacrificing vertical parallax is a reasonable cost to provide holograms with the attributes of the Benton hologram. These attributes include: an image bright enough to be shown in moderate ambient lighting; reconstruction with an extended tungsten light source; reasonable control of spectral to mono-

chromatic color; some if limited control of the parameters affecting image blur¹ and color blur². Artistically that the limited color control and the spectral color is only occasionally related to the image are the most frustrating aspects of the Benton hologram.

5) Multiple Color Laser Transmission Holograms and Multiple Color White Light Reflection Holograms. Since we see all visible wavelengths there is a lighting problem when illuminating colored objects with discrete wavelengths of light. We will probably just have to accept this situation. Three colors are normally used, because the brightness of the image drops off with each added discrete wavelength (by approximately the square of the number of exposures or colors) and because intensity adjustments are necessary in making these holograms and in showing the multicolor laser transmission holograms. Accessible color values are determined by the choice of laser wavelengths. Generally two lasers are used: a helium-neon for red (6328 Å) and an argon ion laser for green (5145 Å) and blue-green (4880 Å). A blue color not proportionally strong as the red and green can be used if there is extra argon ion power to retire. Other combinations giving more color possibilities require the addition of a helium-cadmium laser for a purple-blue or the use of a single rather short life krypton laser for the

¹J.C. Wyant, Opt. Lett. 1,4 (1977).

²H. Chen, Appl. Opt. 17,20 (1978).

three colors. One more preliminary problem then we can get to the technical problems of multi-color laser transmission holograms. Due to low volume demand and short sight the emulsion sensitivity to each of the chosen primary colors is inadequate.

The most prominent technical problem arises because the several superimposed interference patterns image light of any wavelength not just the color with which each was made. From a three primary color hologram we get three images in each color in different places. Only the set corresponding to the location of the original object has faithful color reproduction and automatic registration of the different colors. This imaging problem is called cross modulation or the reconstruction of spurious or ghost images. There are many solutions to this haunting problem. The one producing the highest quality visual results is practically tied to as complicated a system as the one on which it was made. This method is a spectral separation with optical screening. The images, spurious and desired, are reconstructed with carefully aligned and adjusted multiple color laser light. We have mentioned the problems with that procedure. The accurate image has been clarified of overlapping ghost images by a different reference beam angle for each color (separation of spectra). This image is then optically selected and separated by a lensing system with limited angle of view. If this isn't enough to endure to see our beautiful full color laser

light image, this lensing system must be achromatic. Other solutions to the cross modulation problem are: coded reference beams; composite holograms; and volume transmission holograms. In the first method each reference beam is coded differently (randomly diffused by a ground glass screen), causing the ghost image reconstructions to be dispersed into a multicolor background. This shift in the spatial frequencies of the cross modulation noise for the different colors can be effective and the created background noise kept to a minimum by using a small reference angle.¹ Exhibiting this type of hologram is close to impossible with the trivial exception of exactly replacing the plate after processing in the same position in the unchanged coded reference beam. The composite hologram solution also requires correct, though feasible, realignment of the processed hologram with respect to the color array reference beam. Cross modulation is eliminated by making many little holograms each with one discrete color and reconstructing each with only the same color. Volume transmission holograms use a relatively thick emulsion to become frequency selective with a Bragg angle mechanism somewhat like reflection holograms. They are not completely effective in suppressing ghost images and have rather dim images due to the selective

¹R.J. Collier, C.B. Burckhardt, and L.H. Lin, Optical Holography, Student edition (paperback, New York, San Francisco, London, Academic Press, 1971), pp. 508-510.

filtration.

Multi-color volume reflection holograms, one of the more seductive alternatives while having some unsolved problems, are a good example of innovative solution to problems of the same magnitude as the worst we have discussed. This may forecast hope for some methods we have dismissed. The intra-emulsion diffusion-transfer process developed by Dr. Stephen A. Benton is a sophisticated implementation of a simple solution to the emulsion shrinkage/color shift problem of reflection holograms.¹ To eliminate emulsion shrinkage from loss of silver halide during development simply retain all the silver and silver halide in the emulsion. This is effected by getting the unexposed silver halide to migrate to the position of the exposed silver halide. This turns out to be practicable for the short distances within the microscopic interference pattern of a hologram (but not useful for photography). With this process reflection holograms can reconstruct the image in same colors recorded before development. The intra-emulsion diffusion transfer processing (similar to solution-physical development if you have photographic background) increases the diffraction efficiency of the reflection holograms. This is a

¹S.A. Benton, J. Opt. Soc. Amer. 64,1393A (1974); S.A. Benton, "Development Effects in Holographic Imaging", Extended Abstracts of Papers, Tokyo Symposium '77 on Photo- and Electro-Imaging, Tokyo, Japan, 26-30 September 1977.

significant step toward solving the imaging and exhibition problems in ambient lighting conditions. Availability and expense of the chemicals (specifically tetra-methyl reductive acid) used in the last refinement of the intra-emulsion diffusion transfer process is a very real problem, but the 1974 version of the process is accessible. The emulsion's limited color sensitivity remains a hindrance.

Multi-Color Holographic Art Imaging

With an eye on the very real limitations on laboratory facilities available to visual artists a practical, realizable, and inexpensive method of being able to control a full range of colors imaged in space is desirable. We describe the desired qualities of holographic art imaging as: polychromatic imaging with few object depth or placement restrictions; reconstruction with white light for brightness and convenience in exhibition; fabrication with a minimum number of lasers and expensive lenses. Immediate production capability is sought; there will always be the possibility to trade up to more expensive systems and methods. The following developments in color, aperture problems, imaging and image placement for Benton holograms will provide at least one such system.

1) Two Holographic Systems to Produce Multi-Color Benton Holograms. These two systems are similar and so are the resulting holograms. The main difference between the

system using three wavelengths of light and two or three lasers and the system using one wavelength of laser light is convenience. The several laser system enjoys automatic accurate color reproduction (at least for a small range of view) and automatic color registration from the color separation masters common to both systems. The single laser system must be tediously proofed to ensure color and object registration and carefully readjusted to get the desired color combinations to be seen directly in front of the plate. Both have incredible possibilities for artistic imaging: some kind of manipulative control over color, light and space is enough to keep any visual artist intensely involved for a long time. If the single laser system produces a more abstract color (perhaps technically pseudo-color) that is not a deficit, just a difference.

Enough attempted titillation, a description of the multiple wavelength multi-color system follows. The first step is to take color separation masters by lighting the object successively with each coherent laser light color. Then a multiple exposure second generation Benton hologram is made from successive exposure to each master in its respective wavelength. After processing, each exposure images the object and a stacked spectral slit. The imaged objects exactly superimpose and the spectrally dispersed slits are vertically offset or misaligned from each other. When the viewer sees the initial head-on view of the image she per-

ceives the accurately colored image, for the spectrally dispersed slit from the exposure made with green light is offset with the green projected directly in front of the plate. The spectrum for each slit respectively is projected with the color of its recording frequency directly in front of the plate.¹

It is important to notice that the color in the final Benton hologram is effected by three superimposed interference patterns each with an average spatial frequency due to the frequency of the light which made it and to the angle of the reference beam. In the preceding technique the reference angle remained constant while the color changed. Immediately it is obvious that a similar effect can be achieved by changing the reference angle between the exposures and leaving the color constant. That is, the spatial frequency (in the emulsion of the interference pattern) for each exposure which controls the position of the dispersed spectral slit in front of the plate can be controlled by changing the reference angle between exposures from multiple masters. Yes folks here we are, back in the basement again with silk screen color and this color separation holography has just as many possibilities. The actual laboratory set up which should be fairly obvious by now, and the compromises encountered will be explained in part three of this section.

¹P. Hariharan, W.H. Steel, and Z.S. Hegedus, Opt. Lett. 1,1 (1977).

2) Improvements in the Optics of the System. Please recall the problem concerning slit size in the Benton hologram process. (Wide slit yeilds color blurring, narrow slit yeilds speckle.) Imaging the slit at the plate with a cylindrical lens doesn't alter the image information which has been reduced to horizontal parallax. It does however permit relaxed restrictions on the slit width while keeping the image sharp and speckle free, if the image is not near the plane of the hologram. This technique is of great use to form deep-image rainbow holograms. The astigmatism of the Benton hologram is increased by the focusing of the horizontal and vertical aspects of the image at different planes, but the overall effect is of image clarification. The available longitudinal object dimension is not extended by this method.¹

Reconstructing the Benton hologram with a line source or inserting a one dimensional diffuser (an acrylic plane scored in one direction) in the reference beam can reduce the spectral colors in the image or allow extended vertical viewing positions when reconstructed with monochromatic light.² This technique is another color control but not useful for multi-color from one laser.

The one-step Benton hologram offers some imaging possibilities for laboratories with large lenses, however it

¹E.N. Leith and H. Chen, Opt. Lett. 2,82 (1978).

²E.N. Leith, H. Chen, and J. Roth, Appl. Opt. 17,20 (1978).

was not seriously considered here because of the limited undistorted viewing range caused by vignetting. The use of another lens as a field lens (and as a collimator for the reference beam at the same time) counteracts the narrow viewing range. The resulting hologram is useful for images the size of the field lens available.¹

3) Actual Laboratory Procedure and Exhibition of the Images. Accessible color control with limited equipment is demonstrated. Representing the laboratory technique used for several finished images and many discarded ones is a description of making two variations on imagery abstracted from a rose on a prism. The object was carefully chosen and studied through drawing. A larger bulged surface of plastic resin beads was placed behind the dried rose, face down on a prism. Two masters were taken with different lighting (large surface back lit; rose on prism lit from the top and sides) while the object remained unmoved. In the second generation Benton hologram set up (see diagram 1) the slits on the master plates were lit with a converged (by a Fresnel lens) reference beam from a cylindrical lens (a test tube filled with zylene). The beam splitter with micrometer head adjustments was used to direct the reference beam first to one spatial filter then for the second exposure to the other. Test plates were taken for aid in relative color adjustment and registration of the object images in space. One refer-

¹P.N. Tamura, Appl. Opt. 17,21 (1978).

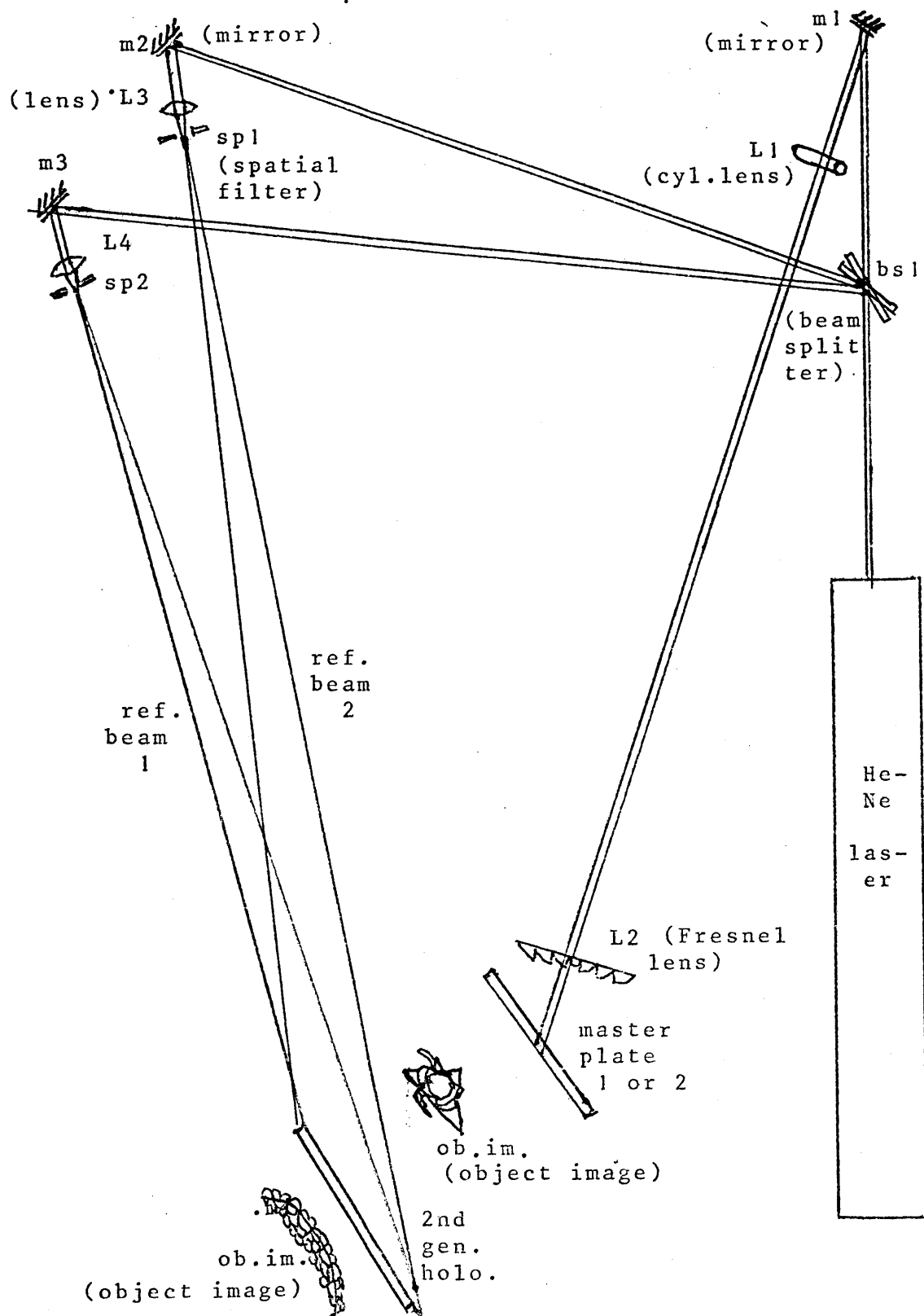


Diagram 1: Multi-Color Benton Hologram Set Up

ence angle was readjusted to get a saturated red with a subdued green background object, a proof plate was double exposed; "Untitled (R.P. Bars)". The Fresnel lens collimator was removed. The image expanded and projected further from the master plate. The next proof plate showed a fringe on the object. A later lab session with the same set up gave a proof plate, "Untitled (Rose Prism)," after test plates and an abstracting of the rose image. For other plates optical composition was effected with no master plate to give a minimal color space image ("Un Gh" and "Un Gh III"). Optical effects derived from the deep image rainbow hologram techniques were used in "Space-Time Simultaneity".

The impressive color images possible with this system mitigate the tedious color selection and awkward registration. Making multiple masters and multiple exposures is time consuming, especially on production runs. Emulsion color sensitivity is no problem because only one color is used. The change in the quality of the color from a technical, at best monochromatic feeling, to complex color spaces and relative color effects is enthralling.

The exhibition was thoroughly designed. The character of the exhibition space was respected and some innovative exhibition techniques and specially designed lighting gave a bright white room with high ambient lighting and bright holographic images.







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